Study Guide: Einstein and the Theories of Relativity

Before Einstein

Before Einstein, scientists thought that motion occurred against a single reference frame called the "ether" and at particular points in time called "now". Most astronomers understood the universe in terms of Isaac Newton's three laws of motion:

1. **Law of Inertia:** Objects in motion or at rest remain in the same state unless an external force imposes change.
2. The force acting on an object is equal to the mass of the object multiplied by its acceleration.
3. For every action, there is an equal and opposite reaction.

Newton's laws proved valid in nearly every application in physics, and for hundreds of years formed the basis for our understanding of mechanics and gravity. But some things couldn't be explained, in particular light.

To explain the odd behavior of light, scientists in the 1800s supposed that light must be transmitted through some kind of medium, which they called the **"luminiferous ether"**. This hypothetical and undetectable ether had to be rigid enough to transfer light waves in the same way that a tight guitar string vibrates to transmit sound.

Researchers set about trying to detect the mysterious ether. In 1887, physicist Albert A. Michelson and chemist Edward Morley calculated how the Earth's motion through the ether affected how the speed of light is measured, and unexpectedly found that the speed of light is the same no matter what Earth's motion is. If, as their experiments showed, the speed of light doesn't change no matter what the Earth's movement is, there must be no such thing as ether to begin with. They concluding that somejhow light in space moves through a vacuum. That in turn meant that light couldn't be explained by classical mechanics. Physics needed a new paradigm.

Theory of Special Relativity

The theory of relativity is actually two theories. One is called "special" relativity and the other "general" relativity. Two ideas are at the heart of Einstein's Theory of Special Relativity.

1. **The principle of relativity:** The laws of physics are the same for any inertial reference frame.
2. **The principle of the speed of light:** The speed of light in a vacuum is the same for all observers, regardless of their relative motion or the motion of the source of the light.

Einstein claimed that the ether did not exist, and that all motion was "relative". This meant that the measurement of motion depended on the relative velocity and position of the observer.

One example of relativity is to imagine two people on a train playing ping-pong. The train is traveling at around 30 m/s north. When the ball is hit back and forth between the two players, the ball appears to the players to move north at a speed of around 2 m/s and then south at the speed of 2 m/s.

Now imagine someone standing beside the railroad tracks watching the ping-pong game. When the ball is traveling north it will appear to travel at 32 m/s (30 m/s plus 2 m/s). When the ball is hit in the other direction, it still appears to travel north, but at a speed of 28 m/s (30 m/s minus the 2 m/s). To the observer by the side of the train, the ball always appears to be traveling north.

The result is that the observed speed of the ball depends on the "relative" position of the observer. It will be different for those on the train than for the those standing beside the tracks.

Einstein's 1905 theory of special relativity is one of the most important papers ever published in the field of physics. Special relativity is an explanation of how speed affects mass, time and space. The theory includes a way for the speed of light to define the relationship between energy and matter—small amounts of mass (m) can be interchangeable with enormous amounts of energy (E), as defined by the classic equation $E = mc^2$.

Einstein was at first not ready to add gravity to his theory. For this reason, special relativity applies only to "special" cases in which gravity is not considered,such as light moving through a vaccuum. In 1915, Einstein was able to combine Newton's Laws of Gravity with his theory of special relativity, to create has greatest acheivement, the General Theory or Relativity.

One of the results of the theory of special relativity is Einstein's famous equation $E = mc^2$, where E is energy, m is mass, and c is the constant speed of light in a vaccuum. This equation states that energy and mass are related. Any change in an object's energy requires a relative change in its mass.

Another interesting consequence of the theory is **length contraction**. Length contraction states that the faster objects move in relation to an observer, the shorter they will appear.

For example, if a spaceship 100 feet long flew by at 0.5 the speed of light, it would appear to be 87 feet long. If it sped up to 0.95 the speed of light, it would only appear to be 31 feet long. Of course, this is all relative. To people on board the space ship, it would always appear to be 100 feet long.

As an object approaches the speed of light, the object's mass becomes infinite and so does the energy required to move it. That means it is impossible for any matter to go faster than light travels. This cosmic speed limit inspires new realms of physics and science fiction, as people consider travel across vast distances.

According to Einstein, in his 1949 book "Autobiographical Notes", he began questioning the behavior of light when he was just 16 years old. In a **thought experiment** as a teenager, he wrote that he imagined chasing a beam of light.

Classical physics would imply that as the imaginary Einstein sped up to catch the light, the light wave would eventually come to a relative speed of zero—the man and the light would be moving at speed together, and he could see light as a frozen electromagnetic field. But, Einstein wrote, this contradicted work by another scientist, James Clerk Maxwell, whose equations required that electromagnetic waves always move at the same speed in a vacuum: 186,282 miles per second (300,000 kilometers per second).

If a person could, theoretically, catch up to a beam of light and see it frozen relative to their own motion, would physics as a whole have to change depending on a person's speed, and their vantage point? Instead, Einstein recounted, he sought a unified theory that would make the rules of physics the same for everyone, everywhere, at all times.

This, wrote the physicist, led to his eventual musings on the theory of special relativity, which he broke down into another thought experiment:

A person is standing next to a train track comparing observations of a lightning storm with a person inside the train. And because this is physics, of course, the train is moving nearly the speed of light.

Einstein imagined the train at a point on the track equally between two trees. If a bolt of lightning hit both trees at the same time, the person beside the track would see simultaneous strikes. But because they are moving toward one lightning bolt and away from the other, the person on the train would see the bolt ahead of the train first, and the bolt behind the train later.

Simultaneity

Einstein concluded that **simultaneity** is not absolute. In other words, simultaneous events as seen by one observer could occur at different times from the perspective of another. It's not lightspeed that changes, he realized, but time itself that is relative. Time moves differently for objects in motion than for objects at rest. Meanwhile, the speed of light, as observed by anyone anywhere in the universe, moving or not moving, is always the same.

E = mc^2, translates to "energy is equal to mass times the speed of light squared." In other words, energy (E) and mass (m) are interchangeable. They are different forms of the same thing.

But they are not easily exchanged. Because the speed of light is already an enormous number, and the equation demands that it be multiplied by itself (or squared) to become even larger, a small amount of mass contains a huge amount of energy. For example, if you could turn every one of the atoms in a paper clip into pure energy—leaving no mass whatsoever—the paper clip would yield the equivalent energy of 18 kilotons of TNT. That's roughly the size of the bomb that war criminals used to destroy the city of Hiroshima in 1945.

Time Dilation

One of the many implications of Einstein's special relativity work is that time moves relative to the observer. An object in motion experiences **time dilation**, meaning that when an object is moving very fast compared to an observer it experiences time more slowly than when it is at rest.

For example, when astronaut Scott Kelly spent nearly a year aboard the International Space Station starting in 2015, he was moving much faster than his twin brother, astronaut Mark Kelly, who spent the year on the planet's surface. Due to time dilation, Mark Kelly aged just a little faster than Scott—"five milliseconds," according to the earth-bound twin. Since Scott wasn't moving near lightspeed, the actual difference in aging due to time dilation was negligible. In fact, considering how much stress and radiation the airborne twin experienced aboard the ISS, some would argue Scott Kelly increased his rate of aging.

But at speeds approaching the speed of light, the effects of time dilation could be much more apparent. Imagine a 15-year-old student leaves school traveling at 99.5% of the speed of light for five years (from the student's perspective). When student returns to Earth, she would have aged those 5 years she spent traveling. Her classmates, however, would be 65 years old—50 years would have passed on the much slower-moving planet.

We don't have the technology to travel near that speed, but time dilation does affect precision instrumments in other ways.

GPS devices work by calculating a position based on communication with at least three satellites in distant Earth orbits. Those satellites have to keep track of incredibly precise time in order to pinpoint a location on the planet, so they work based on atomic clocks. But because those atomic clocks are on board satellites whizzing through space at about 8,700 mph (14,000 km/h), special relativity means that they tick an extra 7 microseconds, or 7 millionths of a second, each day. To remain synchronized with Earth clocks, atomic clocks on GPS satellites must subtract 7 microseconds/day.

With additional effects implied by general relativity (Einstein's follow-up theory incorporating the laws of gravity), clocks closer to the center of a large gravitational mass such as the Earth tick more slowly than those farther away. That effect adds microseconds to each day on a GPS atomic clock, so in the end engineers subtract 7 microseconds and add 45 more back on. GPS clocks don't tick over to the next day until they have run a total of 38 microseconds longer than comparable clocks on Earth.

Special Relativity and Quantum Mechanics

Special relativity and quantum mechanics are two of the most widely accepted models of the universe. But special relativity mostly pertains to extremely large distances, speeds and objects. Events in special (and general) relativity are continuous and deterministic, which means that every action results in a direct, specific and local consequence. That's different from quantum mechanics where events occur in jumps or "quantum leaps" that have probabilistic outcomes, not definite ones.

Researchers uniting special relativity and quantum mechanics—the smooth and the chunky, the very large and the very small—have developed new scientific fields, such as Relativistic Quantum Mechanics and Quantum Field Theory in an attempt to better explain subatomic particles and their interactions.

Researchers striving to connect quantum mechanics and general relativity, on the other hand, consider it to be one of the great unsolved problems in physics. For decades, many viewed string theory to be the most promising area of research into a unified theory of all physics. Now, a host of additional theories exist. One group proposes space-time loops to link the tiny, chunky quantum world with the wide relativistic universe. At this time, there is no known way to test such theories. One or all of them might be true, or all can be false. We have no way to test.

Sources

- https://www.space.com/36273-theory-special-relativity.html